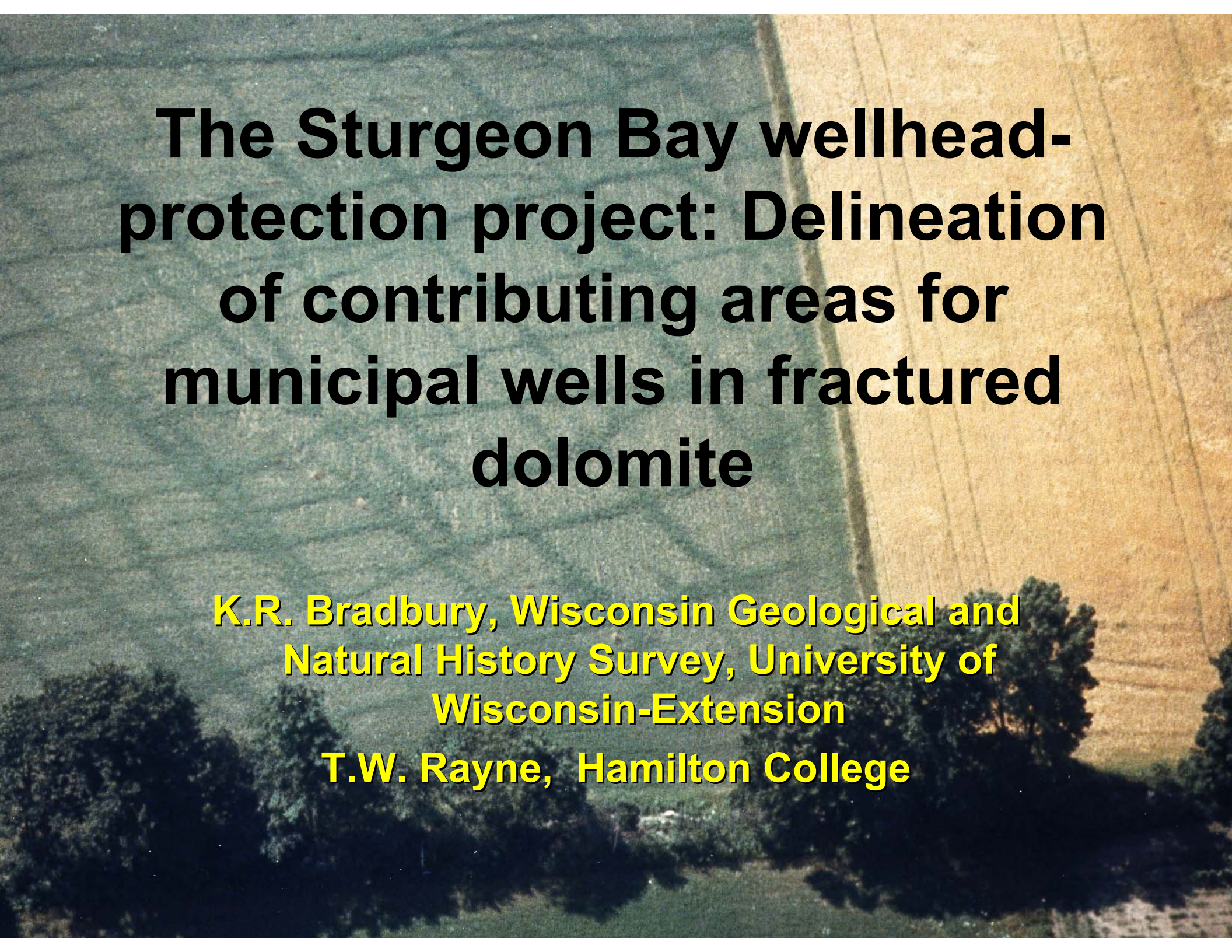
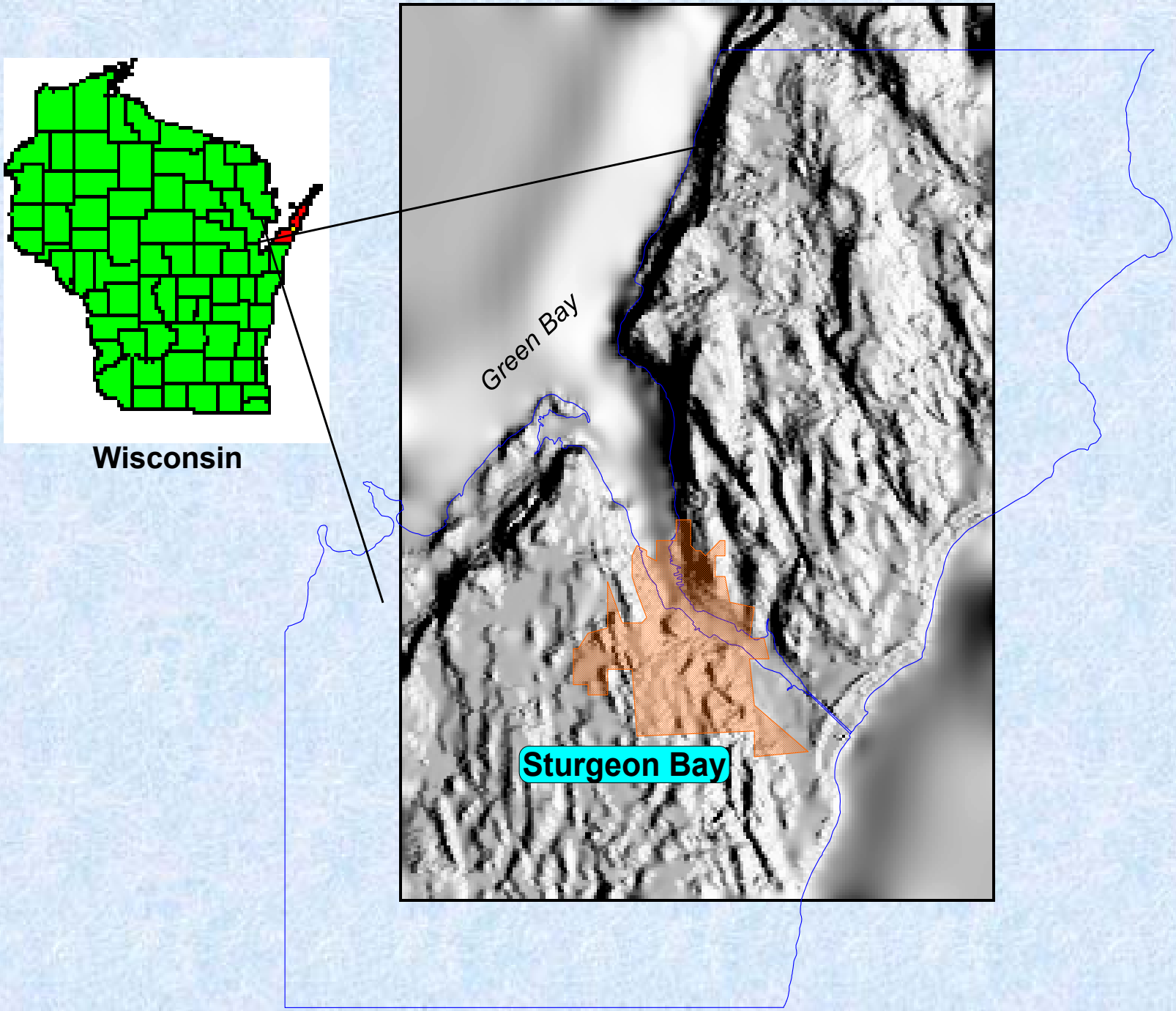
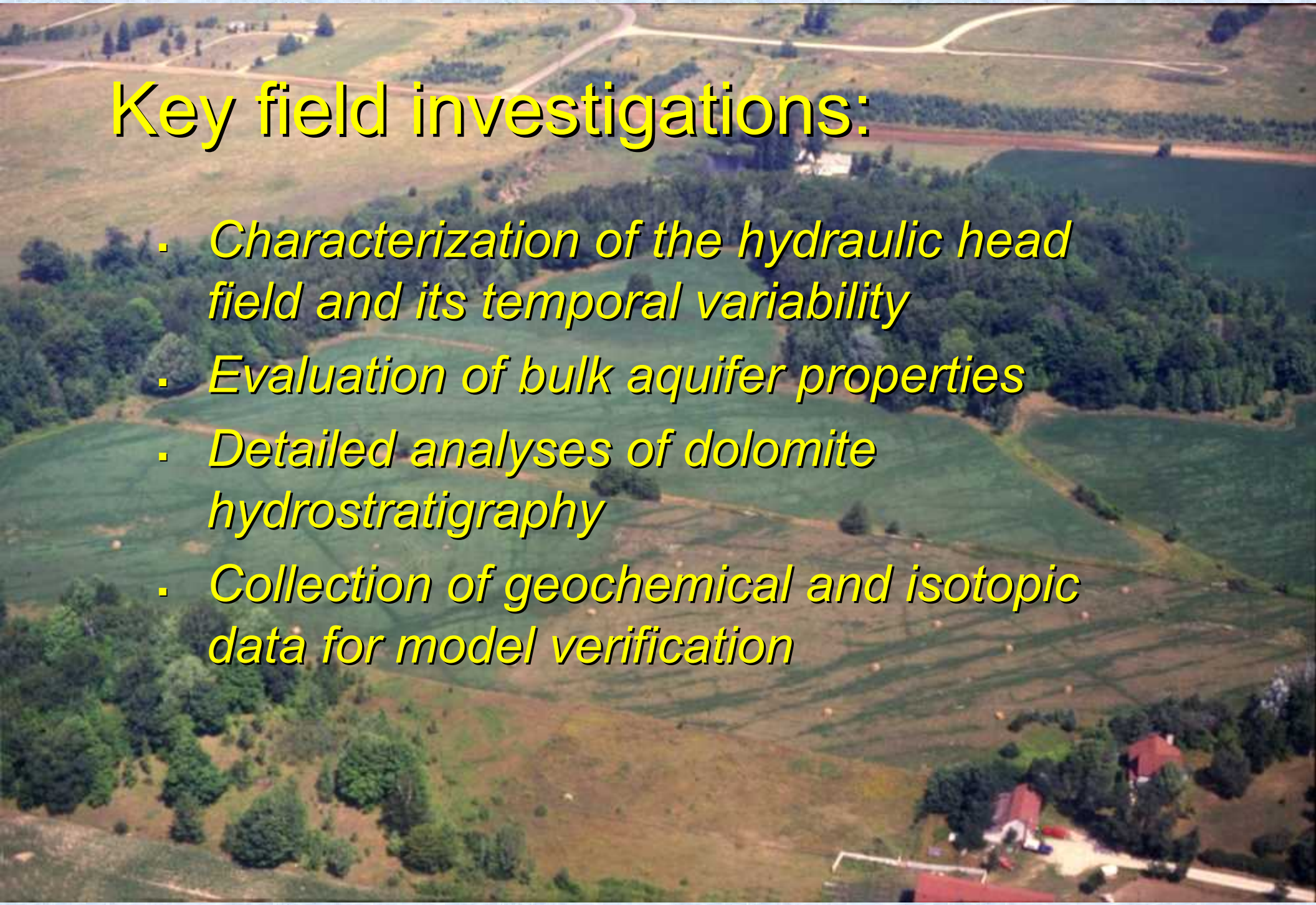


The Sturgeon Bay wellhead-protection project: Delineation of contributing areas for municipal wells in fractured dolomite

K.R. Bradbury, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension

T.W. Rayne, Hamilton College


Wisconsin
Green Bay
Sturgeon Bay

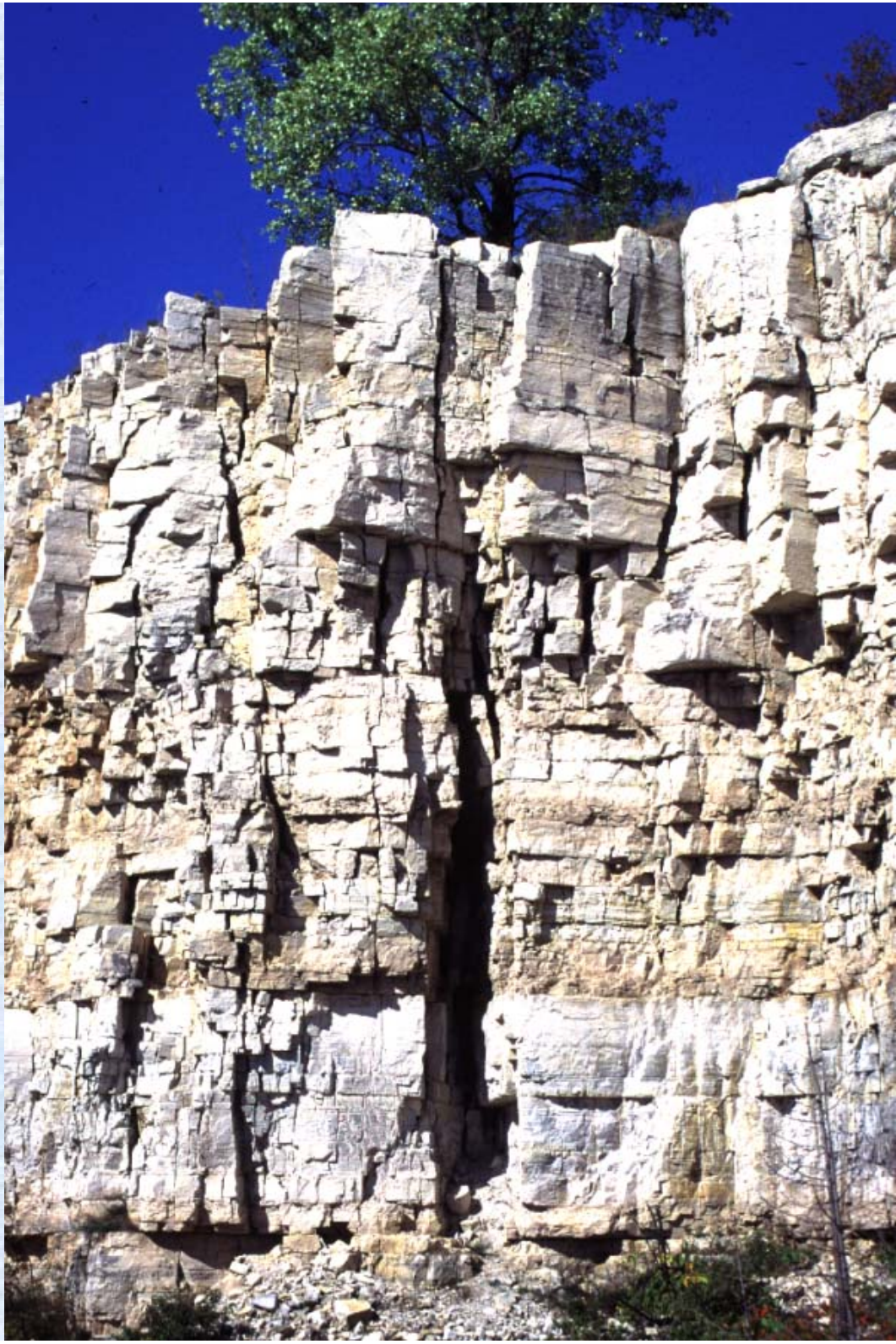


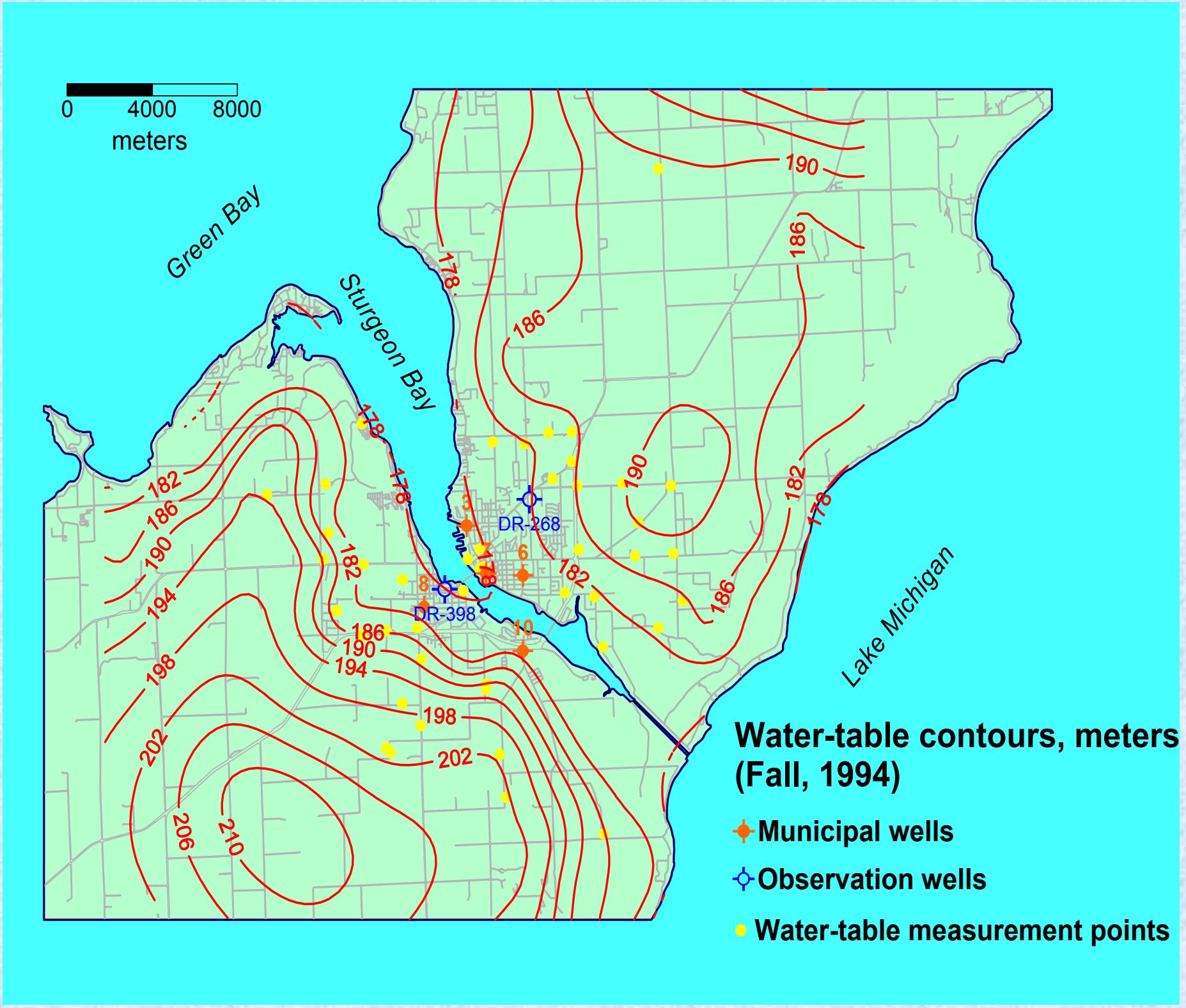
Key field investigations:

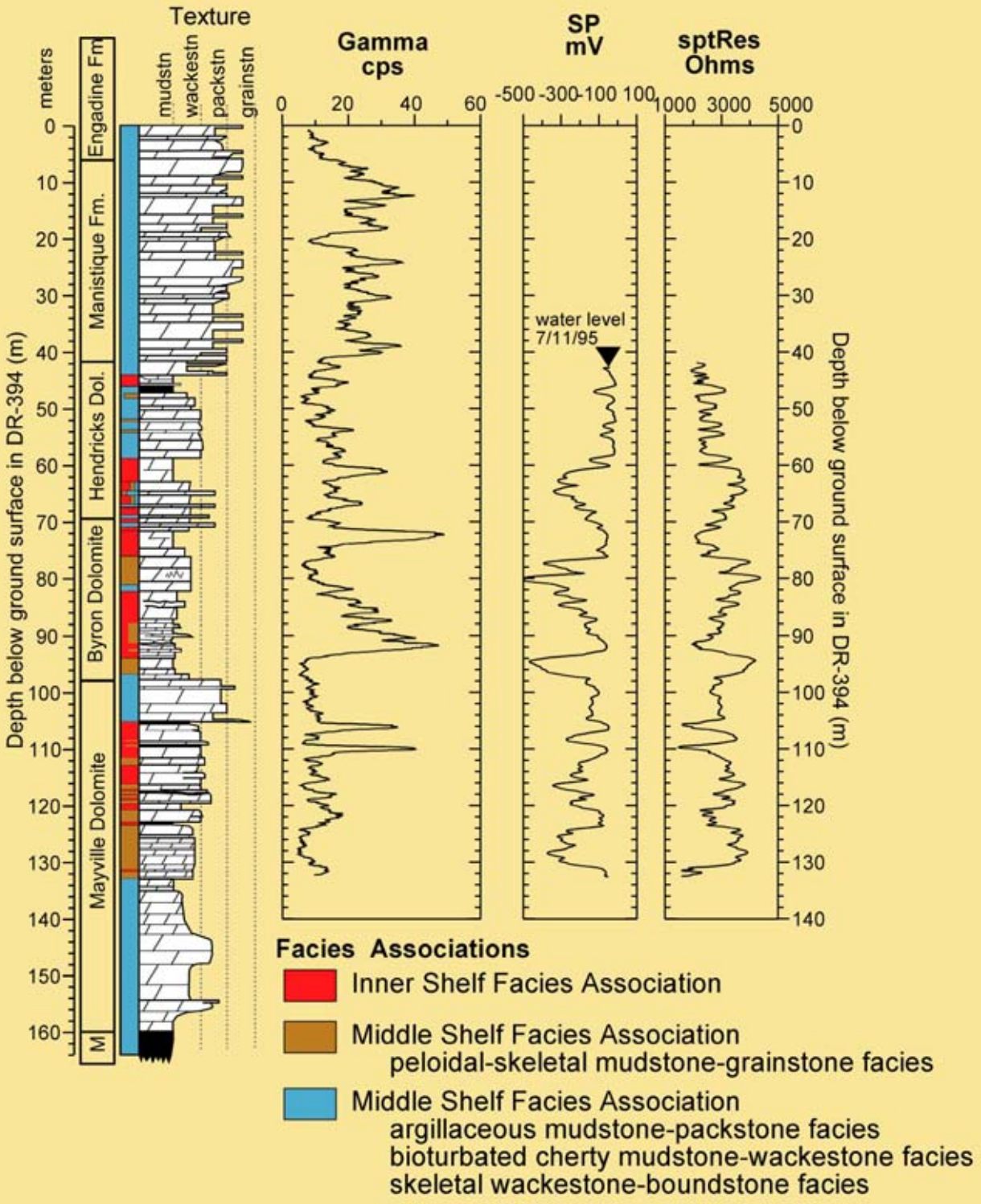
- *Characterization of the hydraulic head field and its temporal variability*
- *Evaluation of bulk aquifer properties*
- *Detailed analyses of dolomite hydrostratigraphy*
- *Collection of geochemical and isotopic data for model verification*

Take-home messages

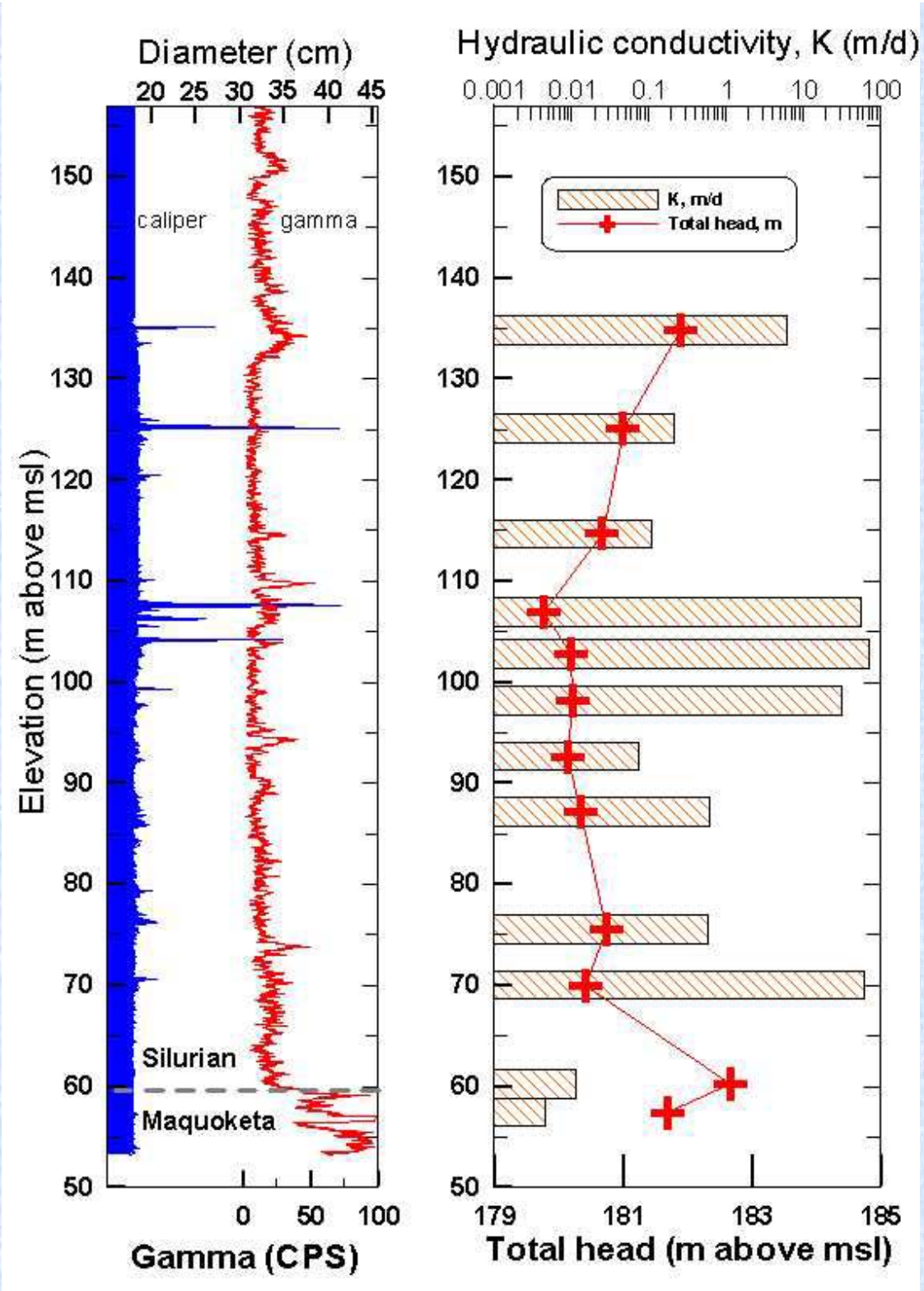
- Bedding-plane fractures form long, continuous flow zones and can be correlated in the subsurface
- A MODFLOW model can simulate these features
- Simulated ZOCs are very large
- Geochemical and isotopic data provide a means of model verification



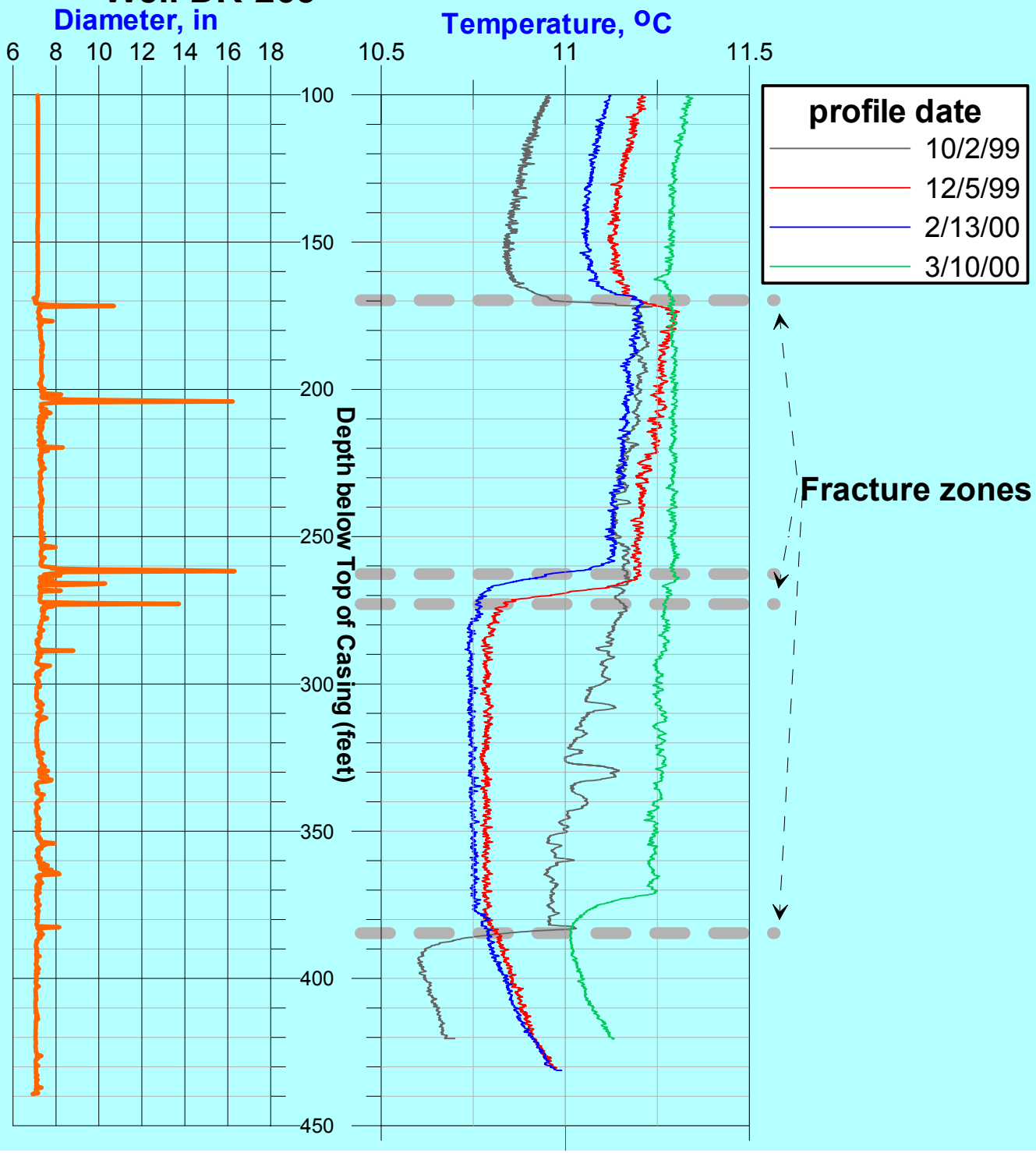

0
4000
8000
meters
Green Bay
Sturgeon Bay
Lake Michigan
DR-268
DR-398
6
8
10
178
182
186
190
194
198
202
206
210
Water-table contours, meters (Fall, 1994)
Municipal wells
Observation wells
Water-table measurement points

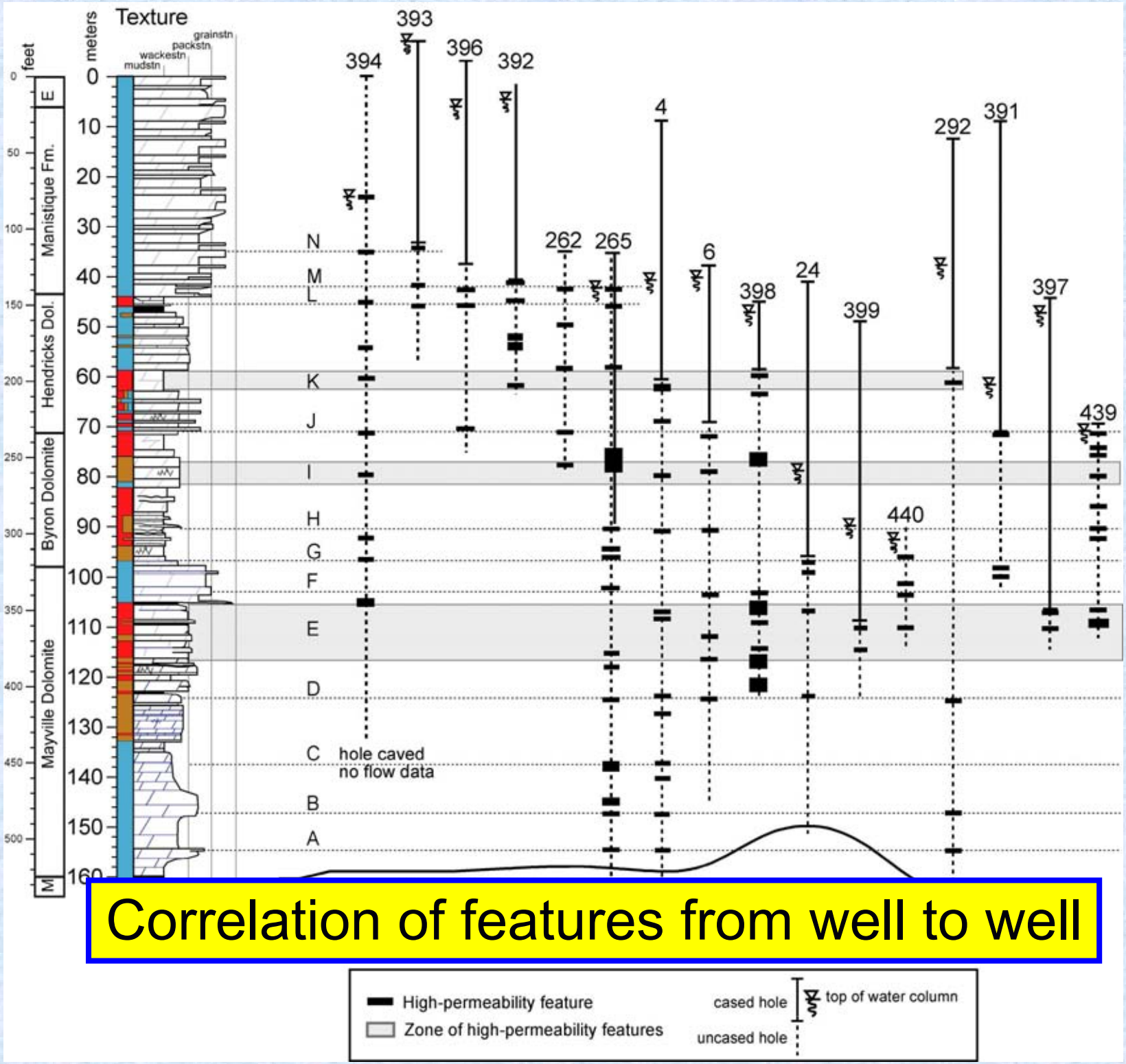

Texture
mudstn
wackestn
packstn
grainstn
meters
Engadine Fm
Manistique Fm.
Hendricks Dol.
Byron Dolomite
Mayville Dolomite
M
Depth below ground surface in DR-394 (m)
Gamma
cps
0 20 40 60
SP
mV
-500 -300 -100 100
water level
7/11/95
sptRes
Ohms
1000 3000 5000
Depth below ground surface in DR-394 (m)
Facies Associations
Inner Shelf Facies Association
Middle Shelf Facies Association
peloidal-skeletal mudstone-grainstone facies
Middle Shelf Facies Association
argillaceous mudstone-packstone facies
bioturbated cherty mudstone-wackestone facies
skeletal wackestone-boundstone facies

- Straddle-packer tests defined conductive zones
- K ranges over 4 orders of magnitude
- Hydraulic head differs by zone

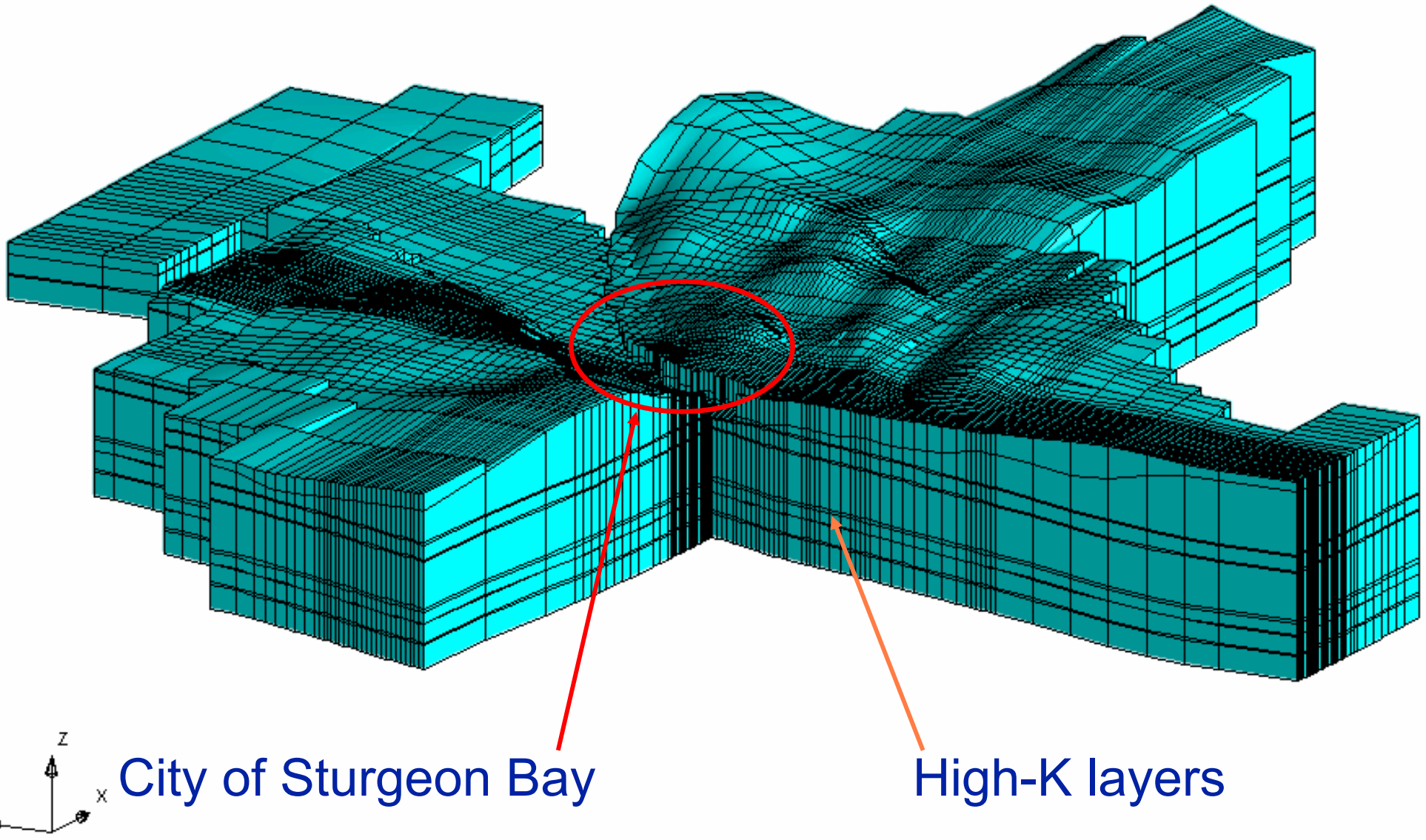


Sequential temperature logs
Well DR-265

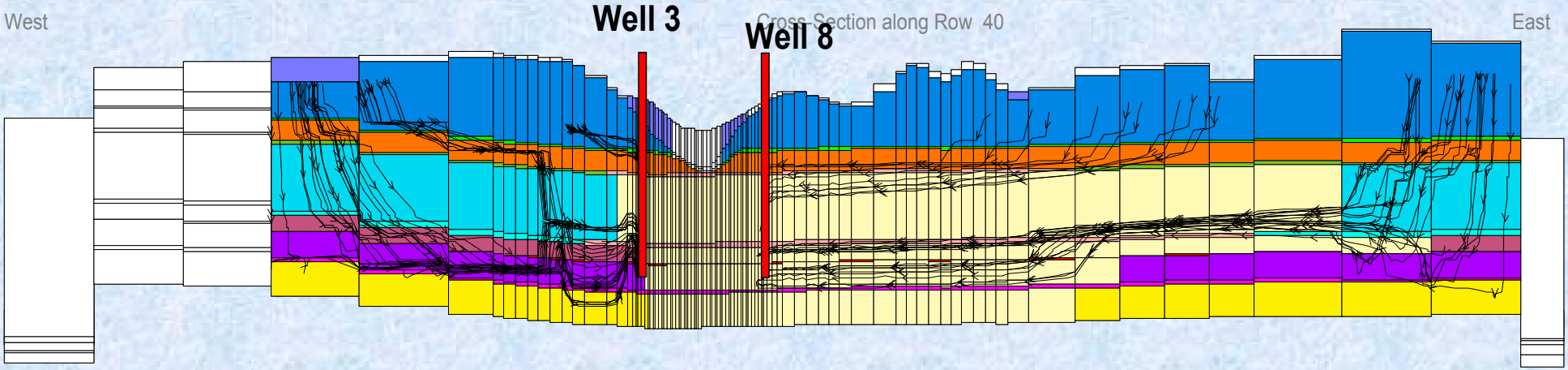


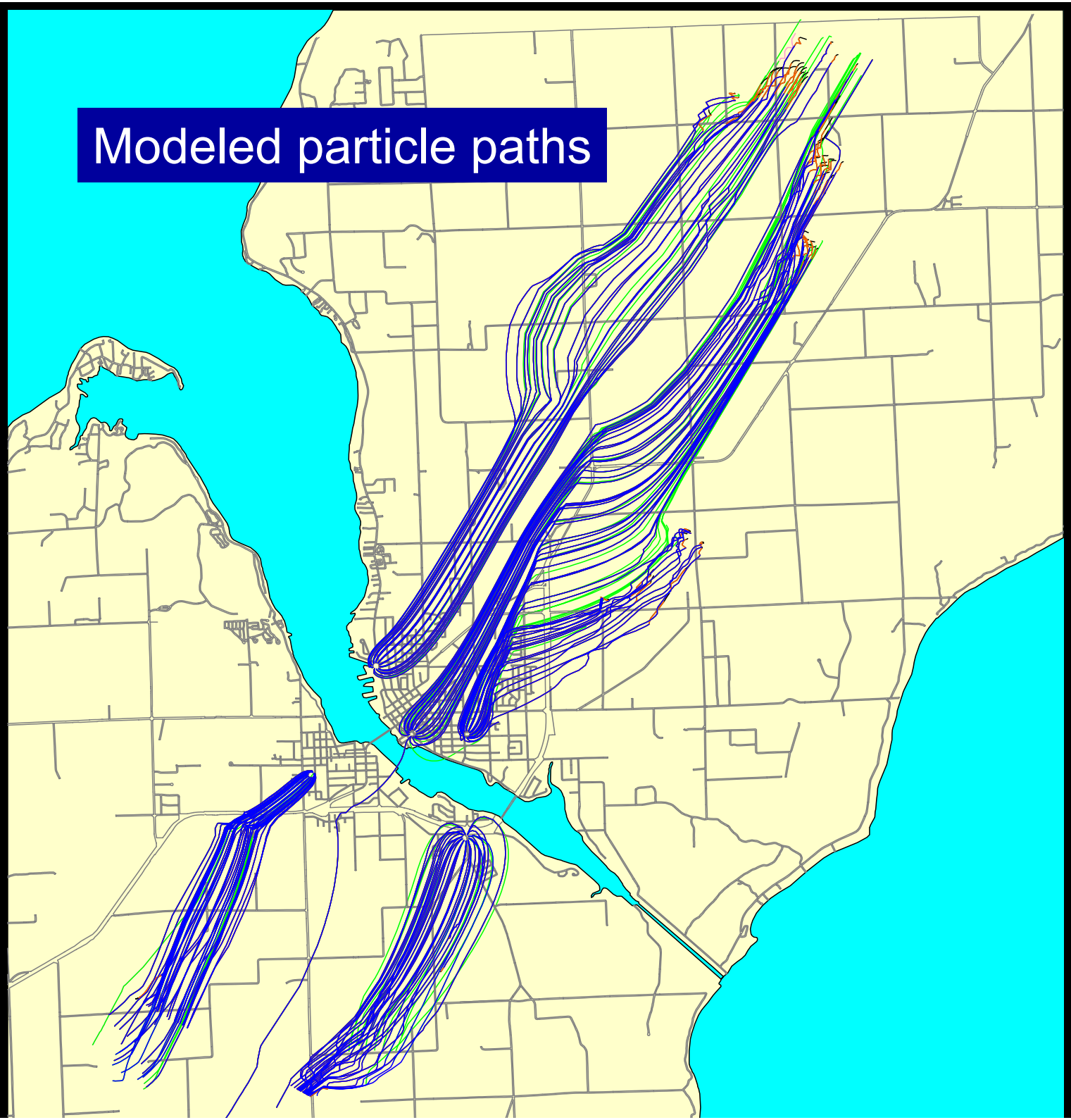

Texture
grainstn
packstn
wackestn
mudstn
feet
meters
Manistique Fm.
Hendricks Dol.
Byron Dolomite
Mayville Dolomite
E
M
N
M
L
K
J
I
H
G
F
E
D
C
B
A
hole caved
no flow data
394
393
396
392
262
265
4
6
398
24
399
440
292
391
397
439
Correlation of features from well to well
High-permeability feature
Zone of high-permeability features
cased hole
top of water column
uncased hole

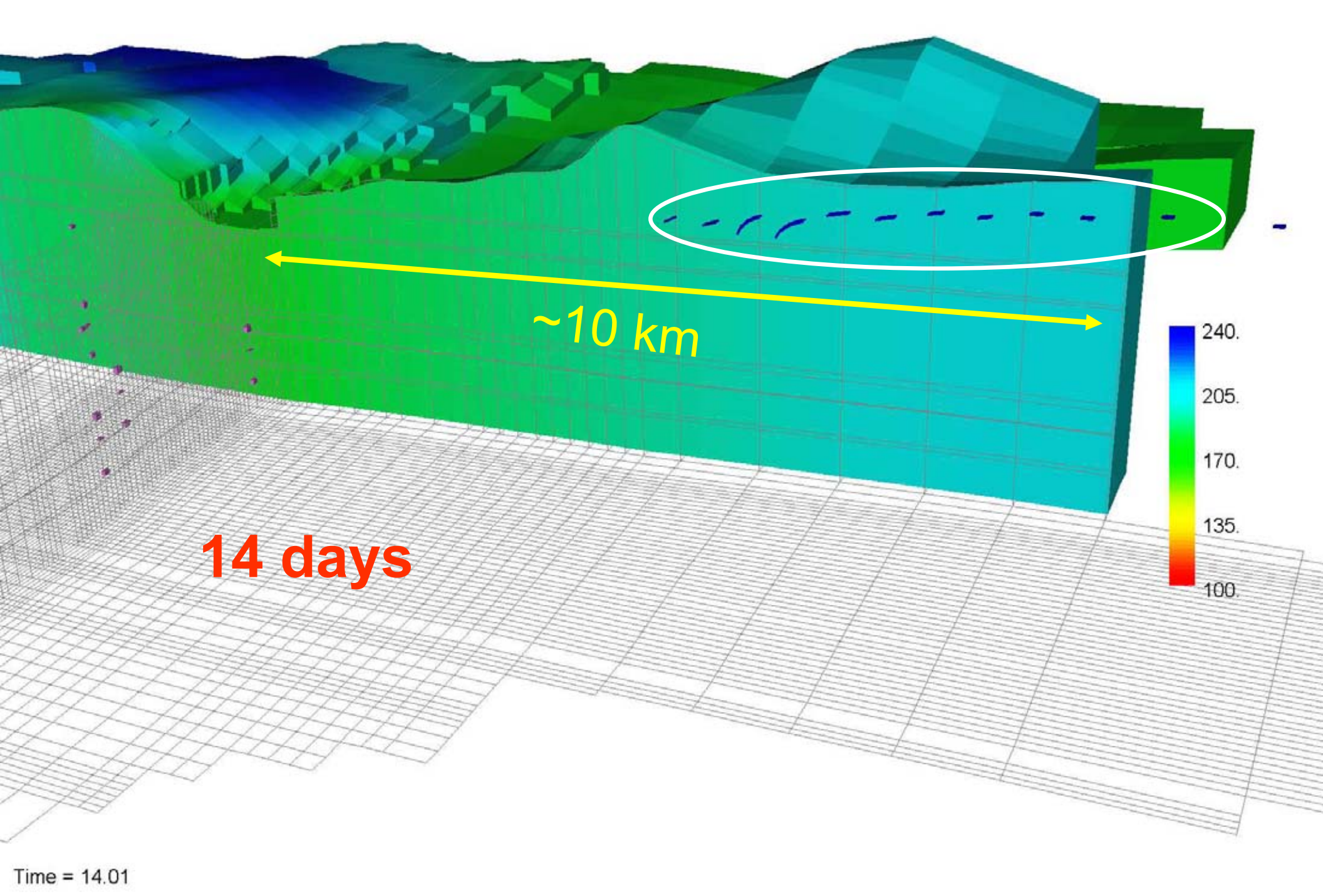
Sturgeon Bay model grid cutaway

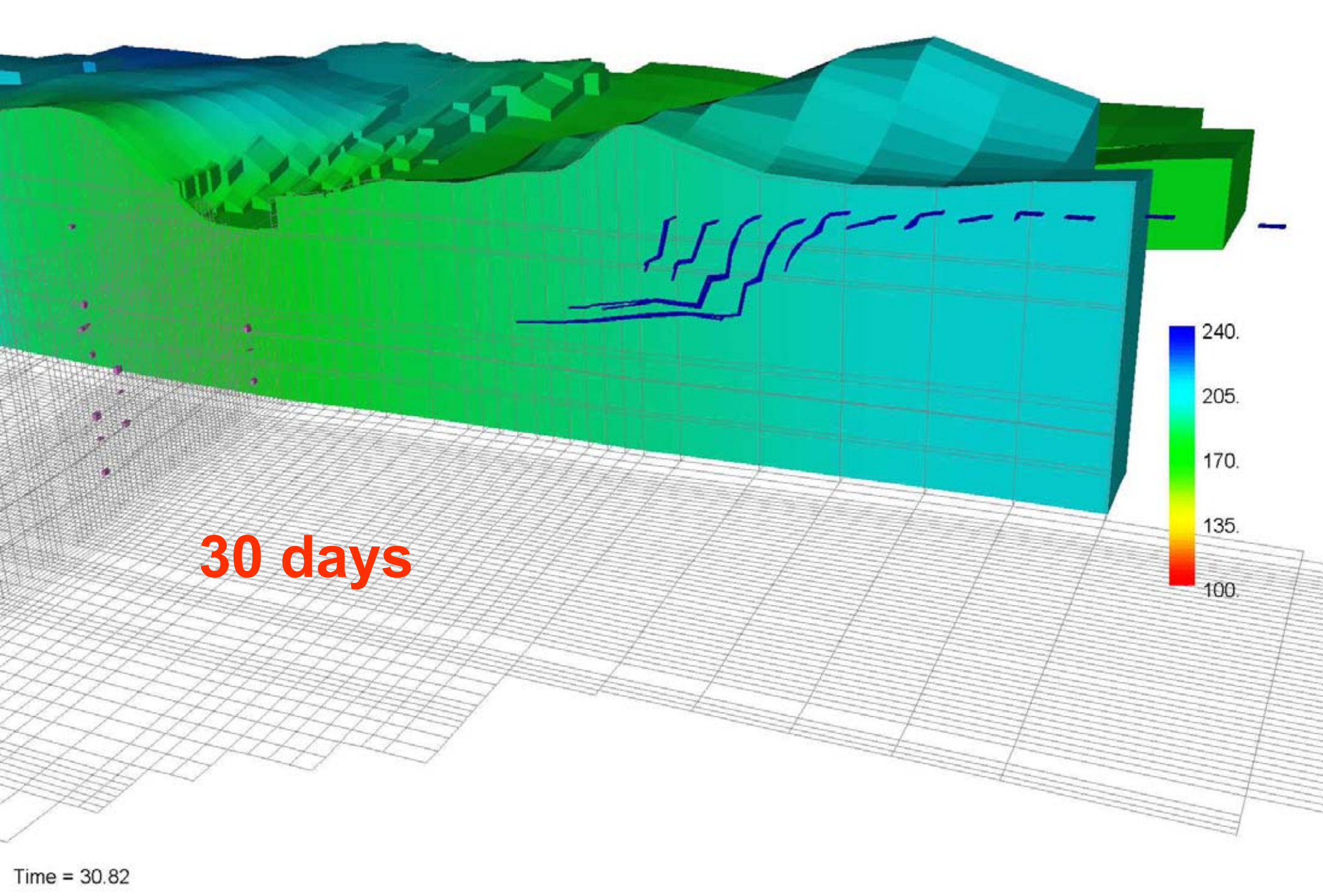


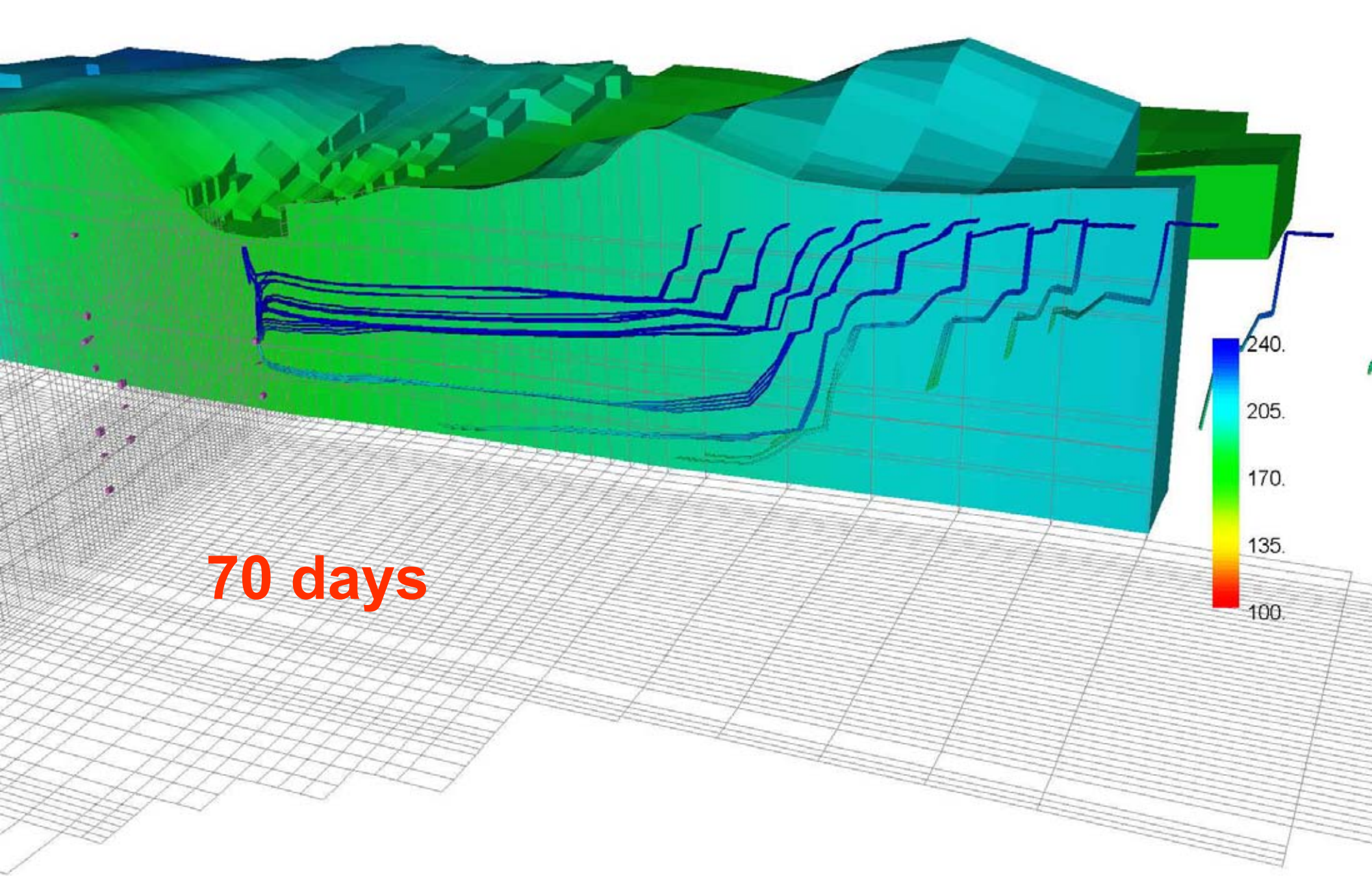
Cross section showing particle tracks

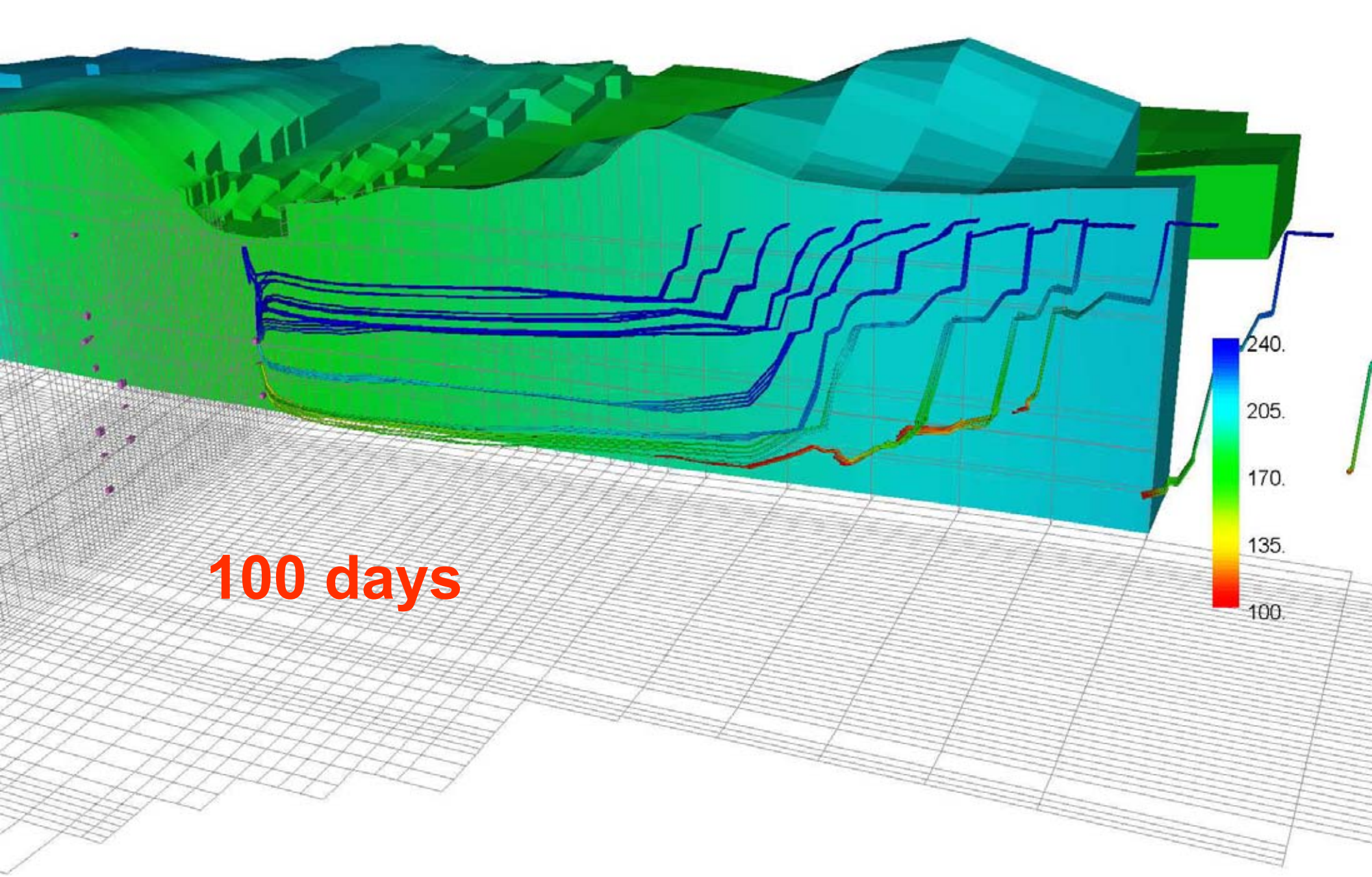


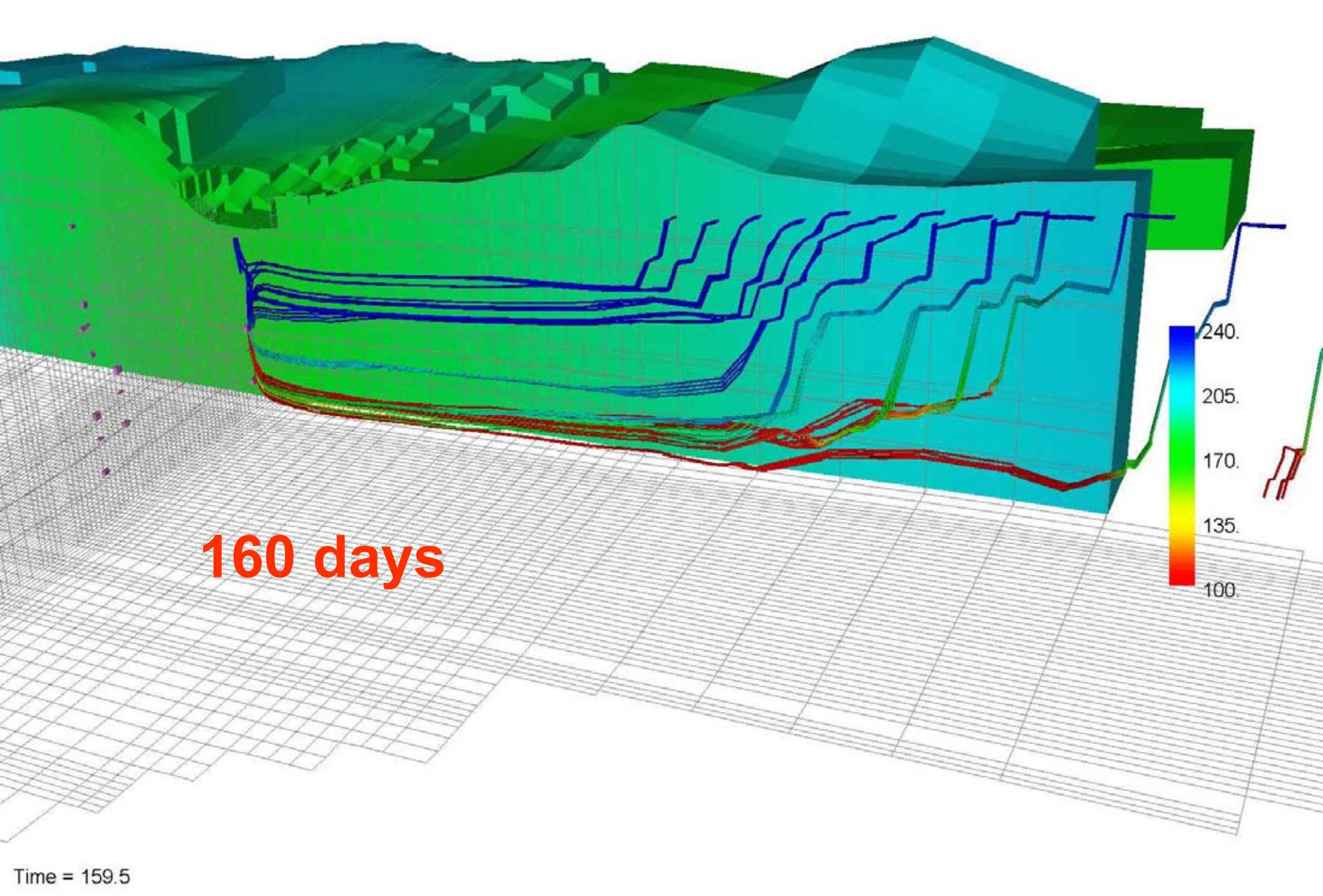

Modeled particle paths

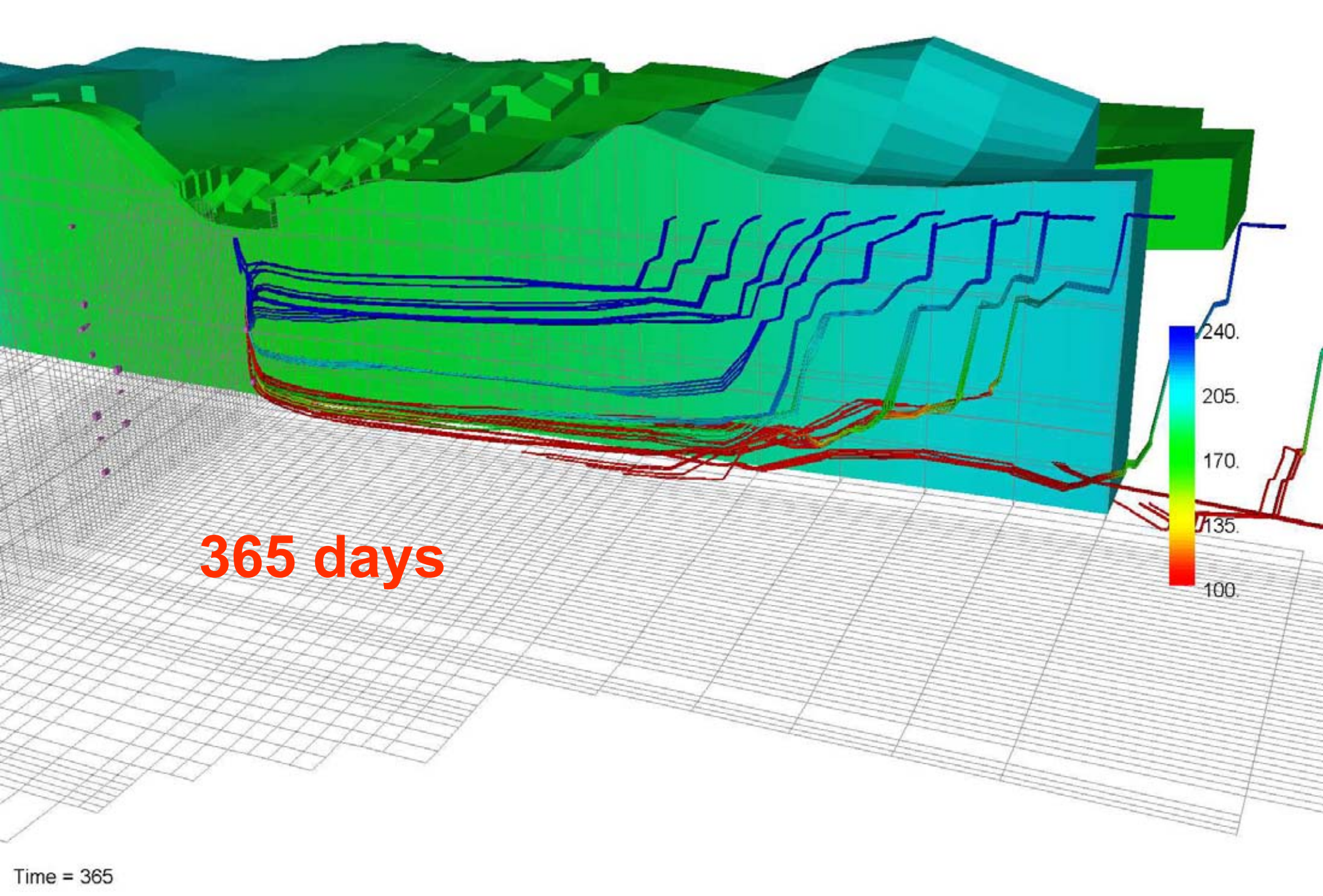

~10 km
14 days
240.
205.
170.
135.
100.
Time = 14.01

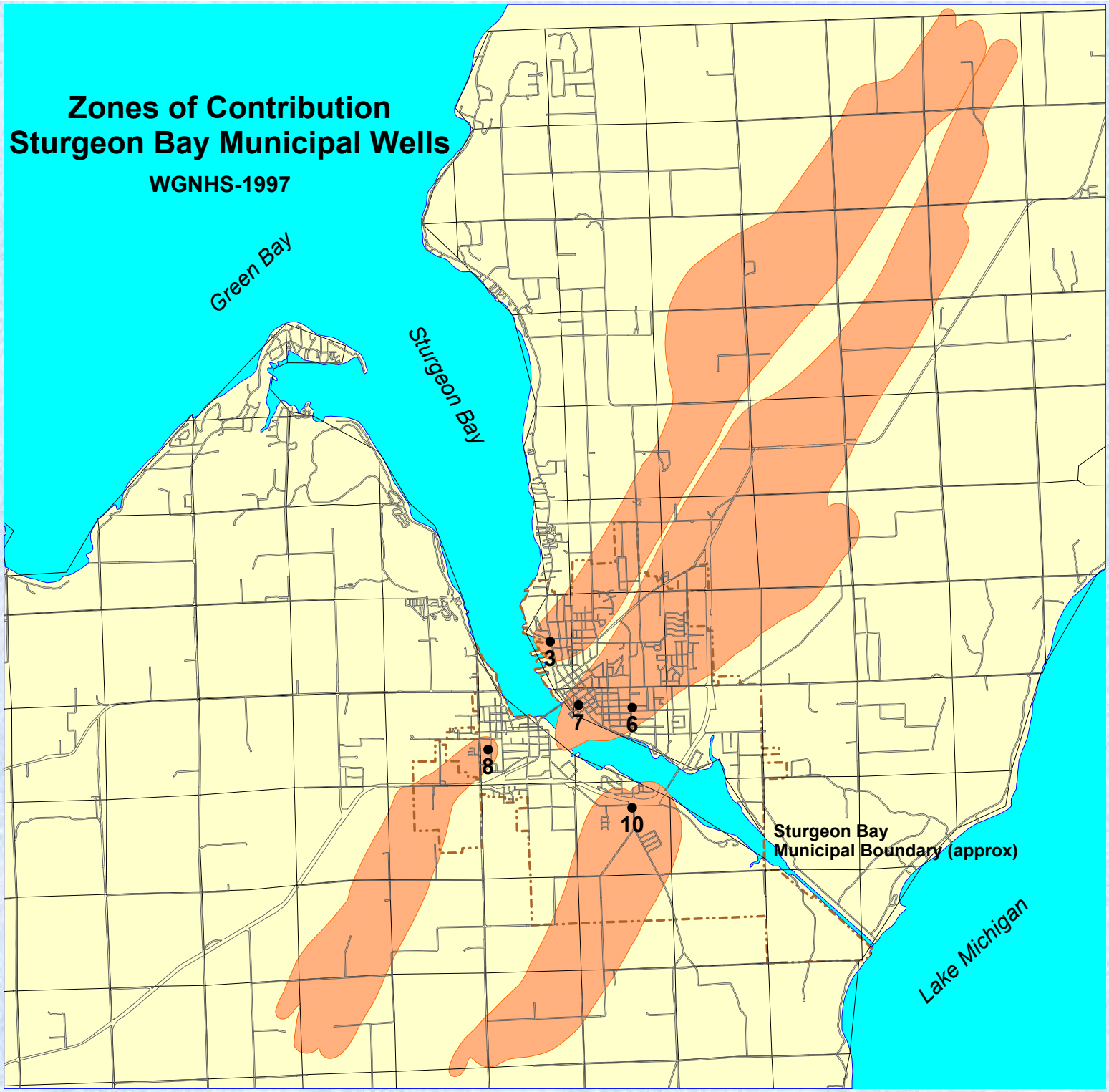

240.
205.
170.
135.
100.
30 days
Time = 30.82


240.
205.
170.
135.
100.
70 days
Time = 69.13


240.
205.
170.
135.
100.
100 days
Time = 100.2


240.
205.
170.
135.
100.
160 days
Time = 159.5


240.
205.
170.
135.
100.
365 days
Time = 365

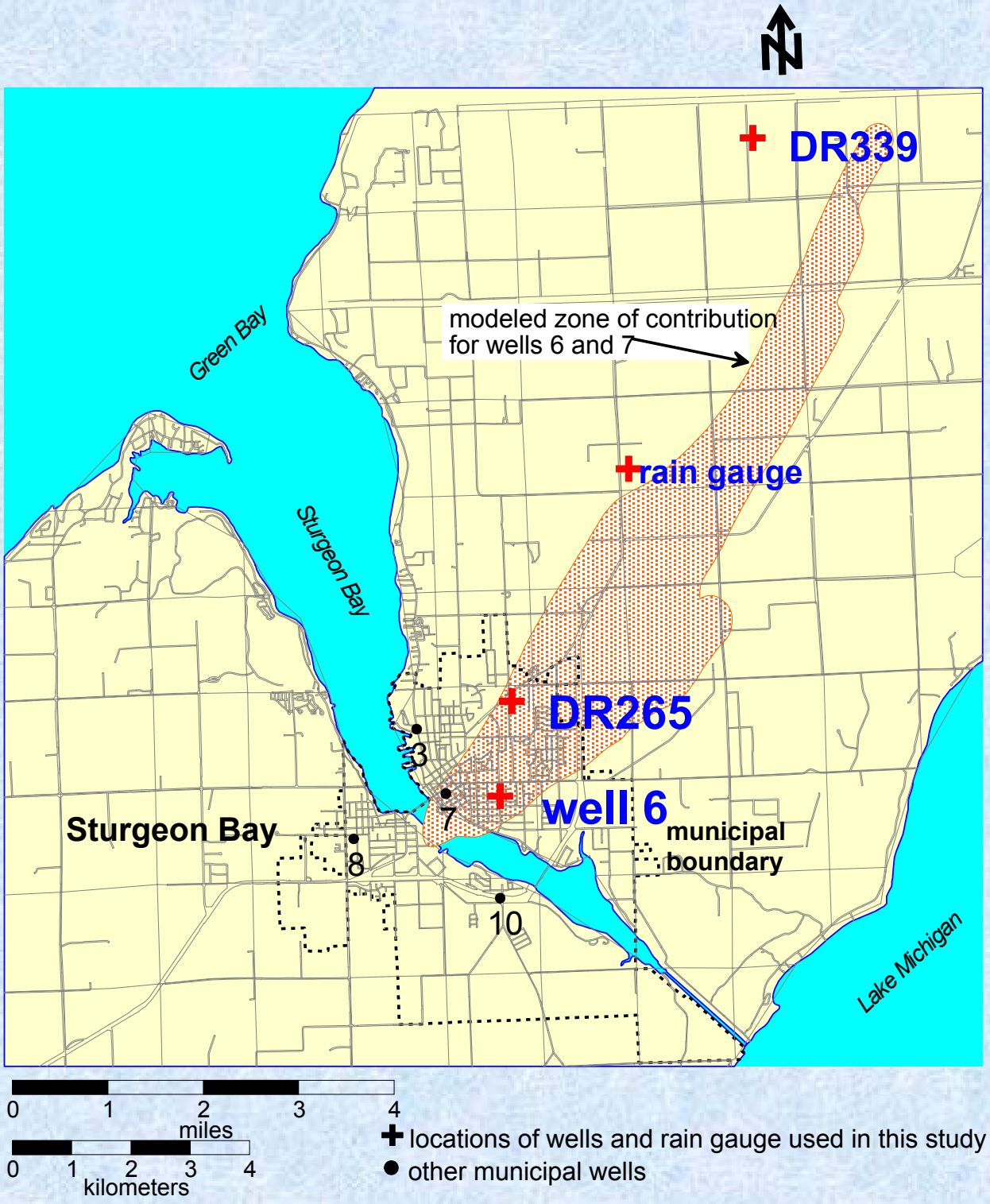

Zones of Contribution
Sturgeon Bay Municipal Wells
WGNHS-1997
Green Bay
Sturgeon Bay
3
7
6
8
10
Sturgeon Bay
Municipal Boundary (approx)
Lake Michigan

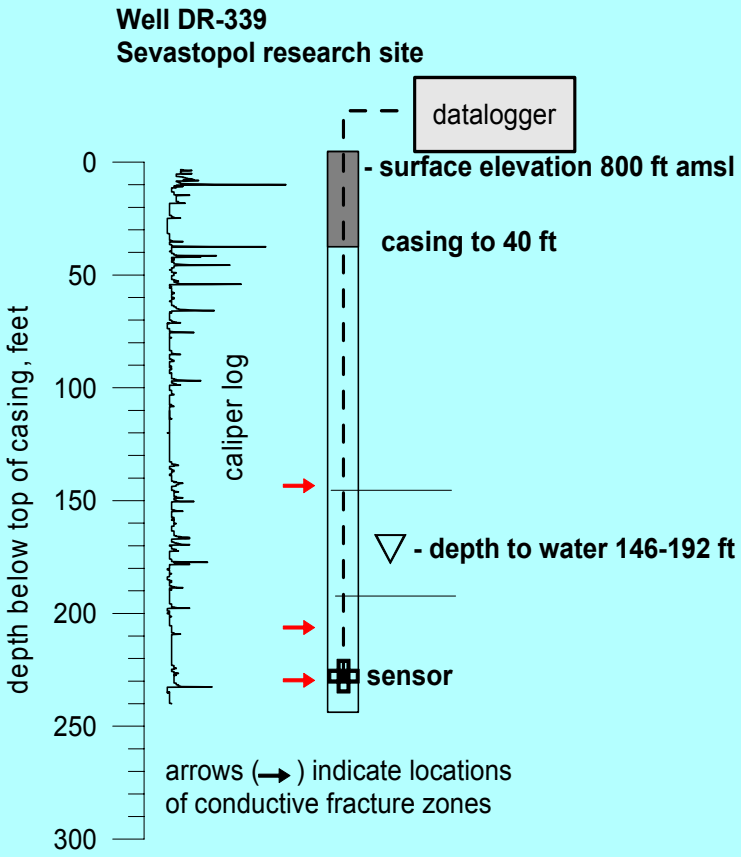
Questions

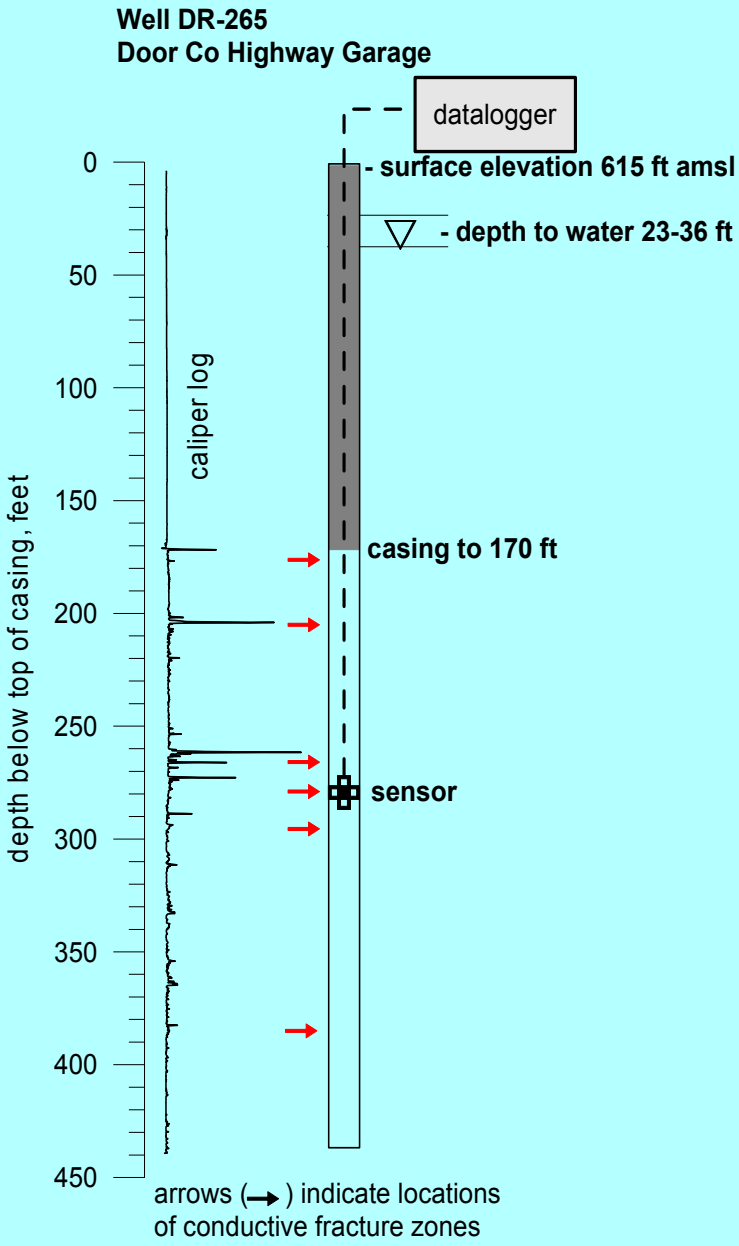
- Is the conceptual model (flow dominated by horizontal fractures) correct?
- Are the model-predicted travel times realistic?
- Can natural tracers help verify travel times?

Hypothesis

- Travel times to the Sturgeon Bay wells are about one year
- There should be an annual signal of variations in T, EC, and ^{18}O in recharge water
- This annual signal should be detectable in groundwater


N
DR339
modeled zone of contribution
for wells 6 and 7
Green Bay
Sturgeon Bay
rain gauge
DR265
well 6
municipal
boundary
Sturgeon Bay
3
7
8
10
Lake Michigan
0 1 2 3 4
miles
0 1 2 3 4
kilometers
locations of wells and rain gauge used in this study
other municipal wells





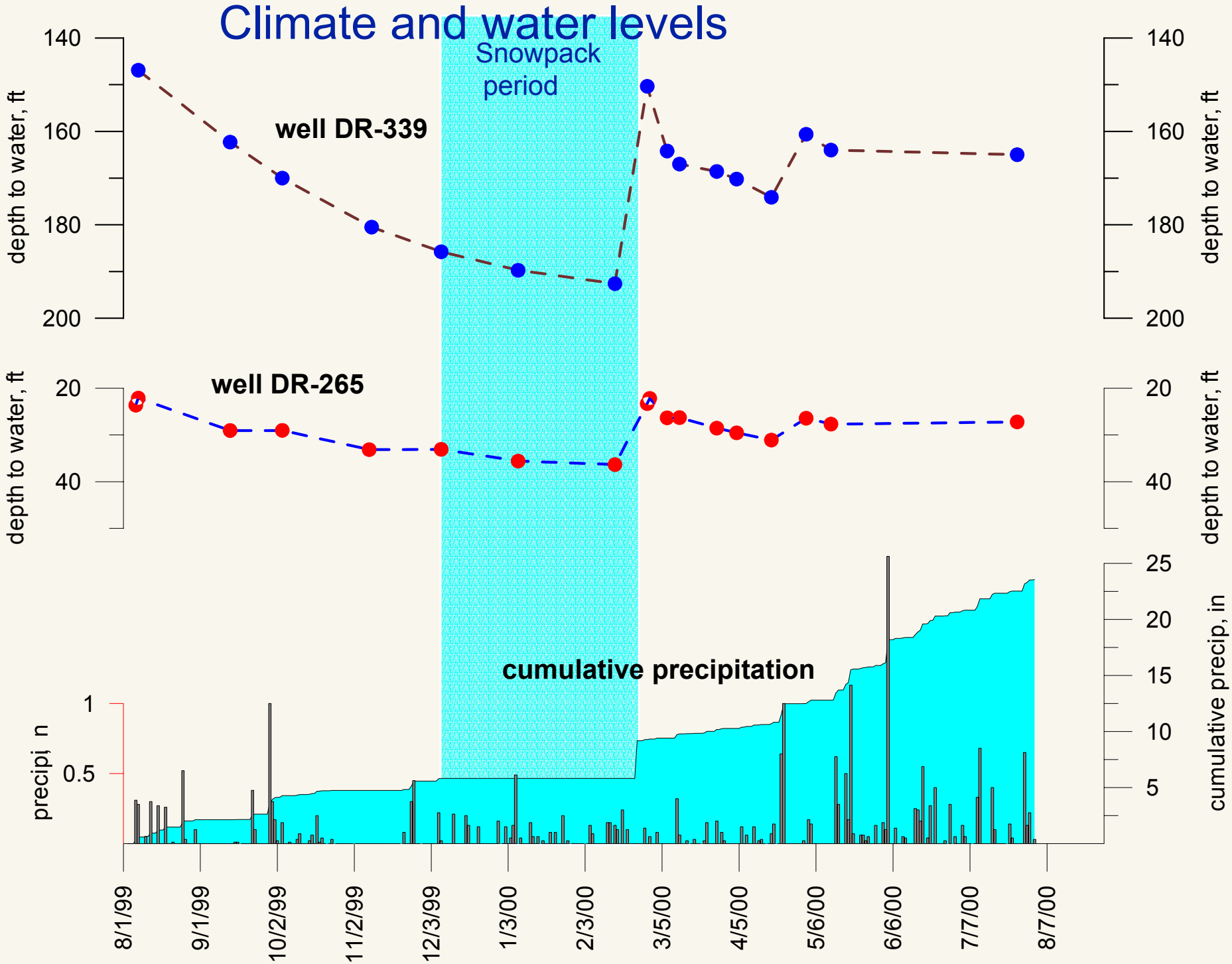
Datalogger placement

Upgradient well location

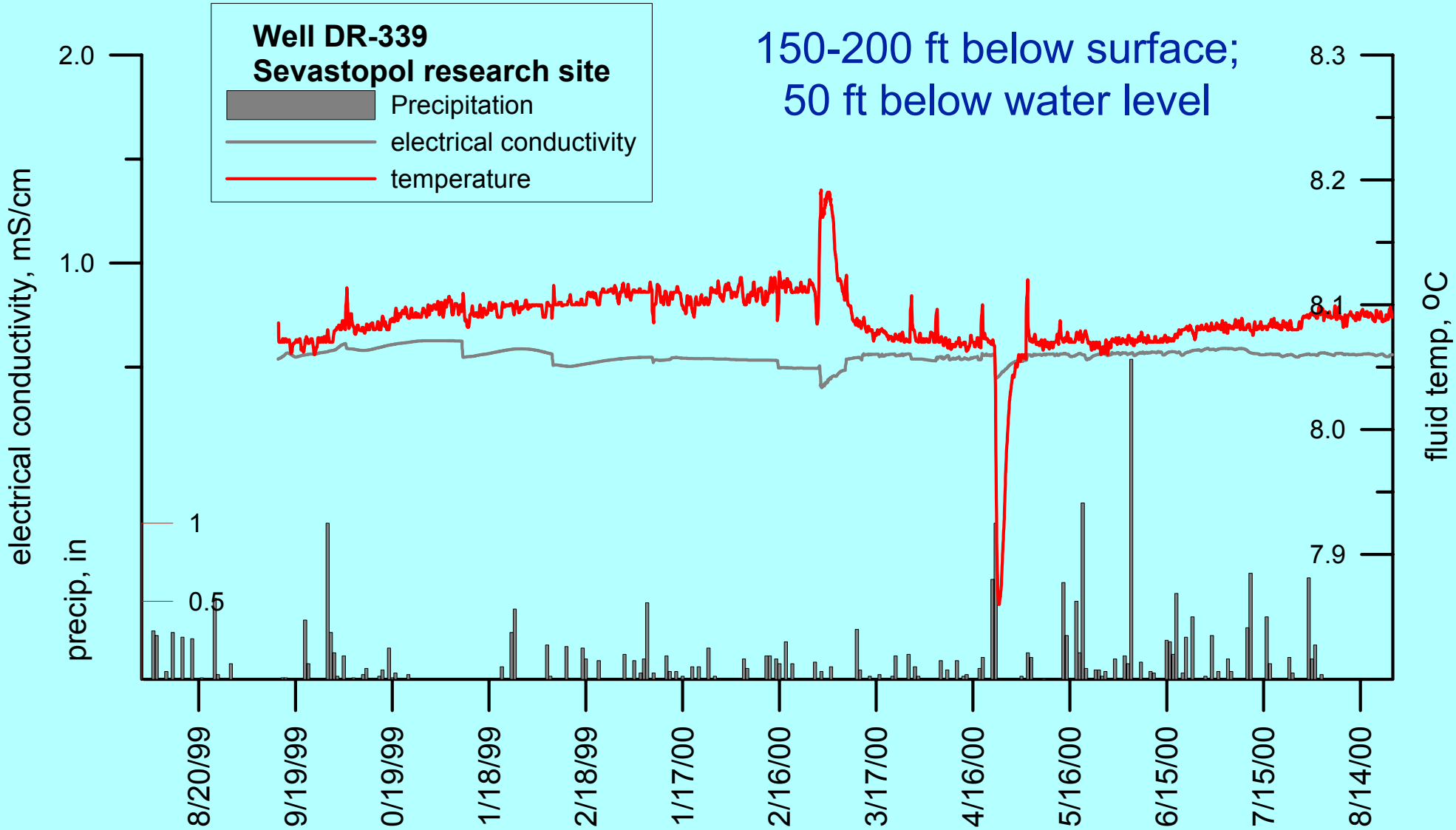
Datalogger setup

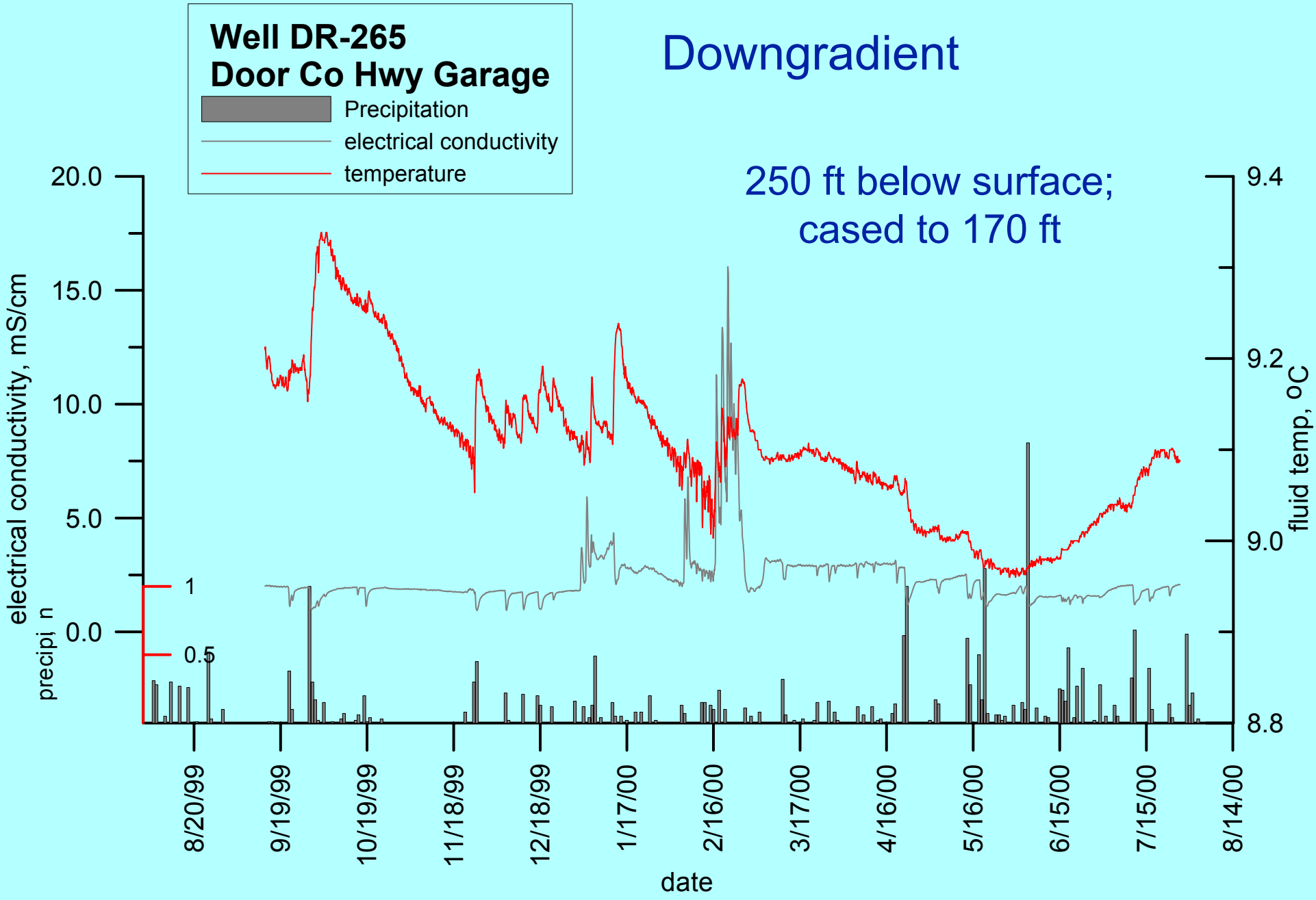
Overall Results

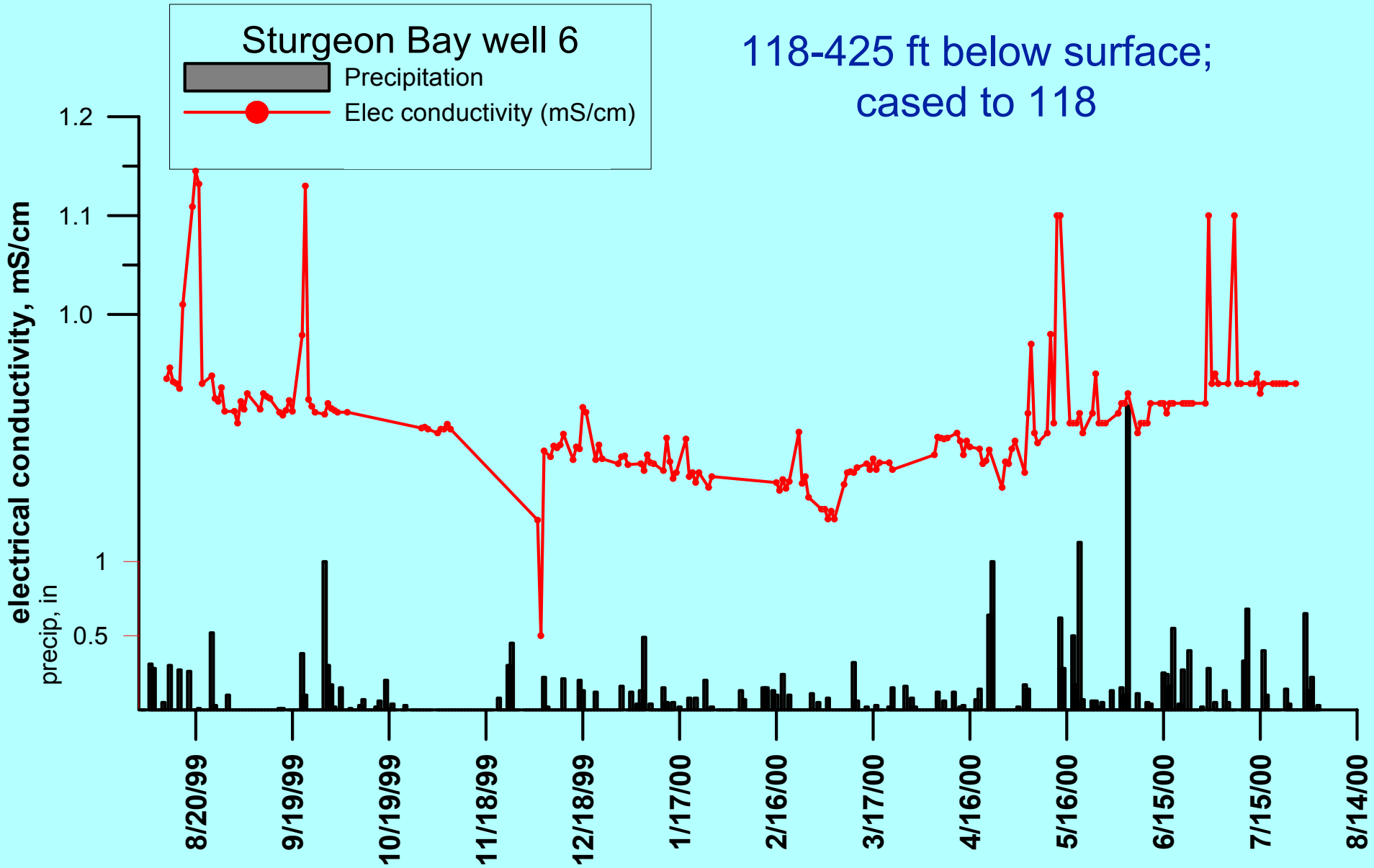
Site	statistic	EC, **uS/cm**	T, **°C**	^{18}O, **permil SMOW**	^{2}H **permil SMOW**
Precip	mean	0.07	7.9	-9.14	-62.8
	SD	0.04	9.8	3.45	32.6
DR-339	mean	0.55	8.09	-11.00	-80.51
	SD	0.04	0.03	0.67	6.00
DR-265	mean	2.32	9.10	-10.13	-72.60
	SD	1.35	0.08	0.60	7.81
SB # 6	mean	0.89		-10.28	-71.30
	SD	0.06		0.25	1.75

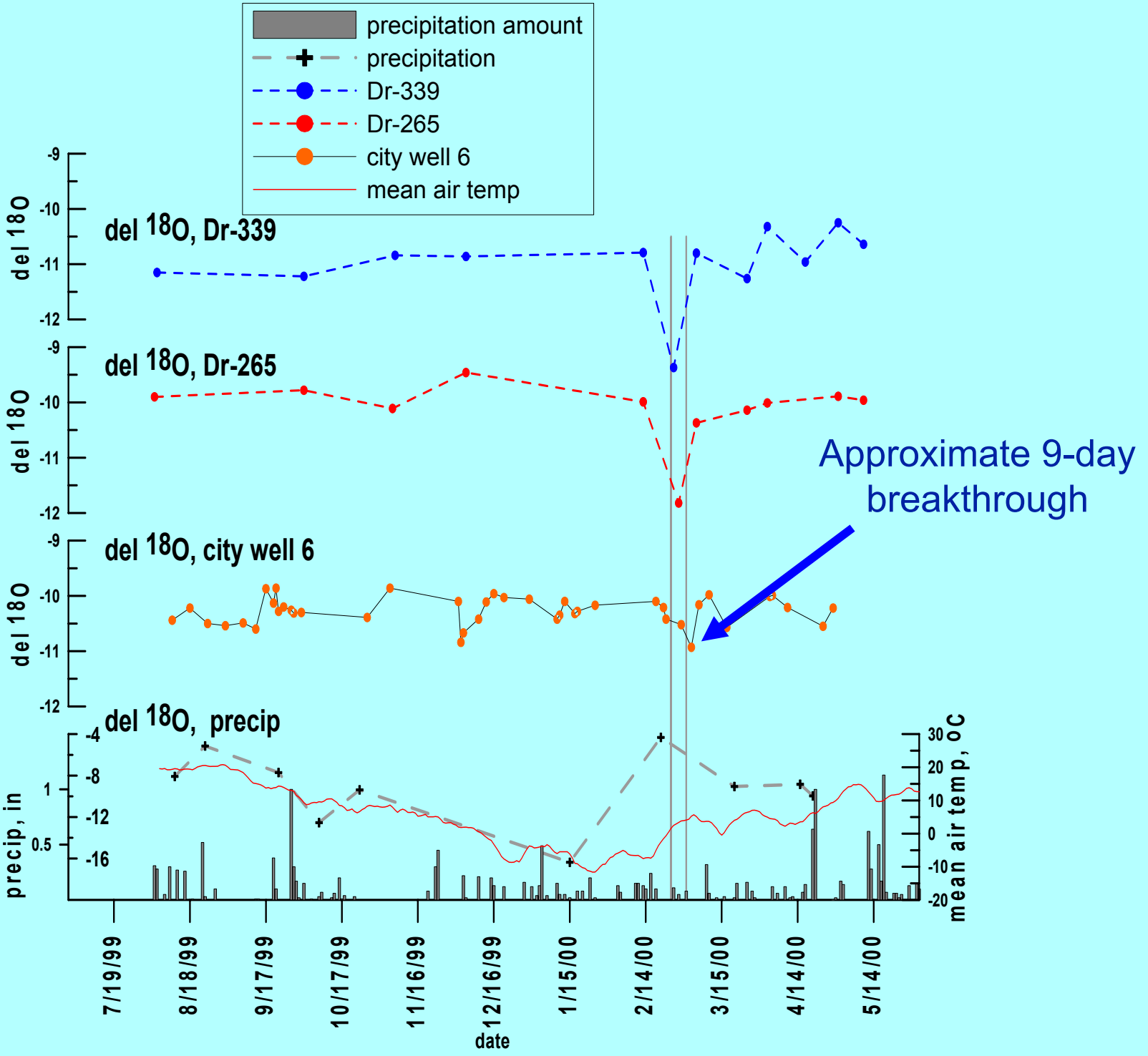

Climate and water levels
Snowpack period
well DR-339
well DR-265
cumulative precipitation
depth to water, ft
precipi n
cumulative precip, in
140
160
180
200
20
40
1
0.5
25
20
15
10
5
8/1/99
9/1/99
10/2/99
11/2/99
12/3/99
1/3/00
2/3/00
3/5/00
4/5/00
5/6/00
6/6/00
7/7/00
8/7/00

Upgradient – recharge area




Well DR-265
Door Co Hwy Garage
Precipitation
electrical conductivity
temperature
Downgradient
250 ft below surface;
cased to 170 ft
electrical conductivity, mS/cm
precipi n
fluid temp, oC
20.0
15.0
10.0
5.0
0.0
1
0.5
9.4
9.2
9.0
8.8
8/20/99
9/19/99
10/19/99
11/18/99
12/18/99
1/17/00
2/16/00
3/17/00
4/16/00
5/16/00
6/15/00
7/15/00
8/14/00
date


Sturgeon Bay well 6
Precipitation
Elec conductivity (mS/cm)
118-425 ft below surface;
cased to 118
electrical conductivity, mS/cm
precip, in
1.2
1.1
1.0
1
0.5
8/20/99
9/19/99
10/19/99
11/18/99
12/18/99
1/17/00
2/16/00
3/17/00
4/16/00
5/16/00
6/15/00
7/15/00
8/14/00

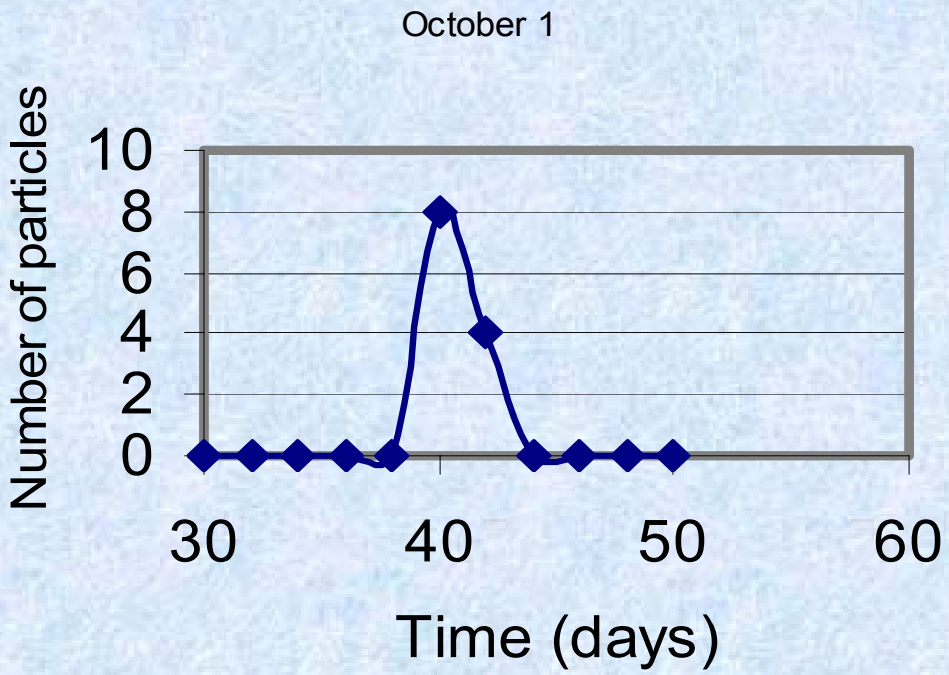

precipitation amount
precipitation
Dr-339
Dr-265
city well 6
mean air temp
del 18O, Dr-339
del 18O, Dr-265
del 18O, city well 6
del 18O, precip
del 18O
precip, in
mean air temp, oC
Approximate 9-day breakthrough
7/19/99
8/18/99
9/17/99
10/17/99
11/16/99
12/16/99
1/15/00
2/14/00
3/15/00
4/14/00
5/14/00
date

Modeling transport

- Simulate movement of water from recharge to city well 6
- Assume conservative tracer; use particle tracking
- Particles (500-1000) released at water table in ZOC of well 6
- Release at low recharge period (Oct) and high recharge period (March)

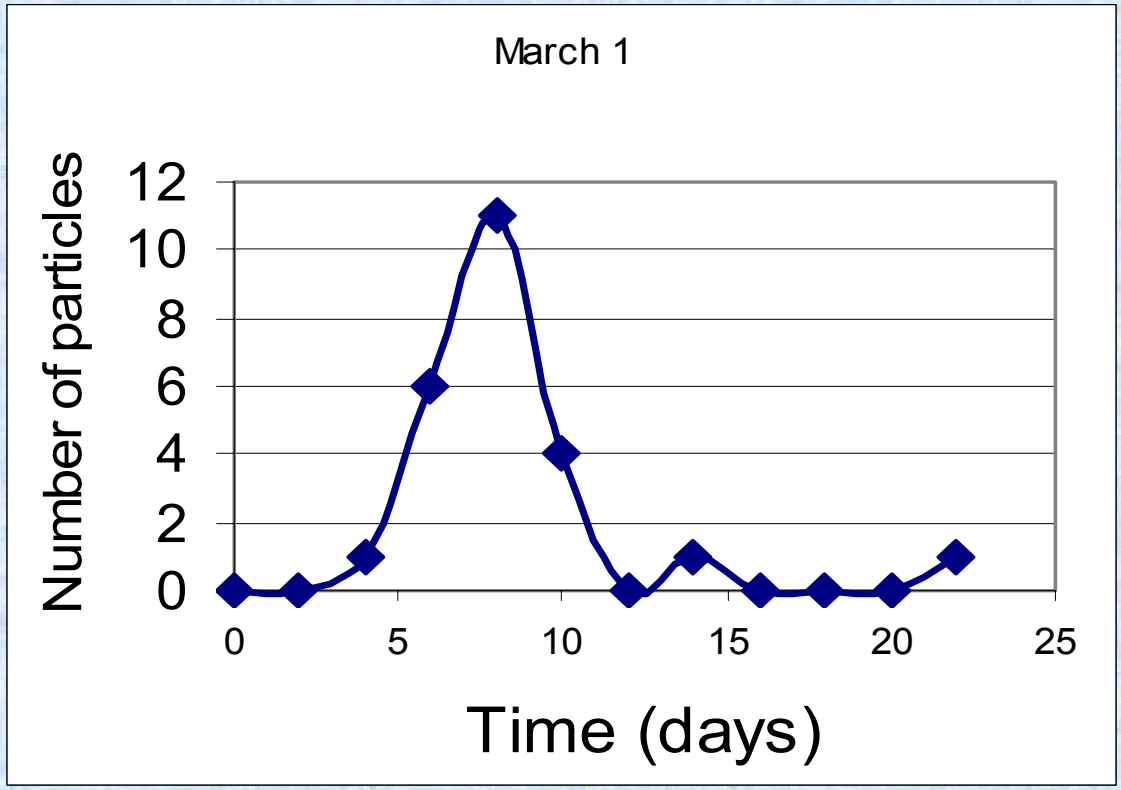
Low recharge results

- Center of mass arrives in 40 days
- Arrival range 38-44 days



High recharge results

- Center of mass arrives in 8 days
- Arrival range 4-11 days



Overall findings

- Field observations, our conceptual model, and numerical simulations show that groundwater flow rates are very rapid (several km/yr)
- Contributing areas for municipal wells can range over many square kilometers.
- The overall transient response of the flow system is consistent with our conceptual model and with numerical modeling results.
- Geochemical and isotopic data are consistent with the results of the conceptual and numerical models.

Some final observations…

- A multi-year, multidisciplinary investigation, **-in cooperation with local officials, the water utility, and residents-** has resulted in findings that are generally accepted
- Implementation of a wellhead protection plan for Sturgeon Bay is currently underway

Further reading…

Rayne, T.W., K.R. Bradbury, and M.A. Muldoon, 2001. *Delineation of capture zones for municipal wells in fractured dolomite, Sturgeon Bay, Wisconsin, USA*. Hydrogeology Journal, 9: 432-450.

Muldoon, M.A, J.A. Simo, and K.R. Bradbury, 2001. *Correlation of hydraulic conductivity with stratigraphy in a fractured dolomite aquifer, northeastern Wisconsin, USA.* Hydrogeology Journal, 9:570-583.